

Cavitation erosion and sliding wear resistance of HVOF coatings

Abstract

The aim of the work was to investigate the resistance to cavitation erosion and sliding wear of as-sprayed HVOF coatings. M(Ni,Co)CrAlY and Cr₃C₂-NiCr based coatings were deposited using HVOF method onto stainless steel substrate grade AISI 304. As-sprayed coatings' surface morphology was examined by SEM-EDS and profilometer methods. Cavitation erosion tests were conducted in distilled water with the use of vibratory rig and stationary specimen method. Cavitation erosion curves were plotted as well as cavitation wear mechanism was observed with the use of SEM microscope. Sliding wear tests were performed using the ball-on-disc tribotester with counter-specimen (ball) made of steel 100Cr6. Wear rates and coefficient of friction were computed. Normalized wear resistance with reference to stainless steel reference sample AISI 304 was calculated. In addition, comparable analysis of wear resistance results was conducted. M(Ni,Co)CrAlY coating presented the highest cavitation erosion resistance, therefore Cr₃C₂-NiCr coating represented the highest sliding wear resistance of all tested materials.

Keywords:

cavitation erosion;
sliding wear;
HVOF;
thermal spraying

Introduction

Thermally sprayed coatings increase the wear resistance of machine and equipment components. The abrasive processes, erosion by solid particles and corrosion processes are the most frequently mentioned wear processes in literature [1÷4]. Systematic research articles on abrasive wear of thermally sprayed coatings are published and these issues seem to be quite well known. However, there are relatively few scientific reports describing issues related to the testing of resistance to cavitation wear of thermally sprayed coatings, using the HVOF (High Velocity Oxygen Fuel) method. The method is mainly used for metal or cermet coatings [4÷10]. In comparison to other thermal spraying processes, e.g. plasma spraying or flame spraying, HVOF spray coatings have a low porosity and homogeneous structure. This is mainly due to the low process temperature and the high speed of the sprayed particles [2,11,12].

The search for coatings with high resistance to cavitation erosion is a current issue, both from a scientific and industrial point of view [6,10,13÷15]. Literature survey indicates that the homogeneous structure of the material has a positive effect on the increase in resistance to cavitation erosion [16÷18].

Therefore, it seems advisable to carry out cavitation resistance tests of thermally sprayed coatings using the HVOF method. The literature describes works describing the resistance to cavitation wear of Cr₃C₂-NiCr cermet coatings applied with the HVOF method [5,6], but there are few papers relating to resistance to cavitation erosion of MCrAlY (M = Ni and/or Co) type coatings. Particularly there is a lack of works which synthesize the results of the abrasive and cavitation tests of HVOF coatings carried out with reference to standard reference materials, for example stainless steel.

The aim of the research was to assess the resistance to cavitation erosion and abrasive wear of HVOF coatings.

Material and methods of research

The test material consisted of two thermally sprayed coatings with supersonic velocities (HVOF) on a stainless steel substrate of AISI 304 grade (X5CrNi18-10 according to PN-EN), from which reference samples were made. Coatings of type M(Ni, Co)CrAlY (designated as Z2) and CrC-NiCr (designated

as Z3) were sprayed onto steel pins with a diameter of $\varnothing 25$. M(Ni,Co)CrAlY type thermally sprayed coatings are mainly used as bond-coatings, anti-oxidation and high temperature corrosion protection coatings, while Cr_3C_2 -NiCr coatings are used to provide, among others, corrosion resistance, erosion resistance and abrasion resistance.

The morphology of the coatings was characterized by observing the surface using a Phenom World Pro-X scanning microscope (SEM-EDS, Phenom-World). The surface roughness of the coatings was measured after spraying using the Dektak 150 contact profilometer from Veeco Instruments, Inc. (rounding radius of the measuring needle 2 μm). An analysis of chemical composition was performed in selected micro-areas using the SEM-EDS method.

Cavitation tests were carried out using a vibratory apparatus using a stationary specimen method (in accordance with ASTM G-32). The distance between the tip of the sonotrode and the sample was 1 mm. The tests were carried out in distilled water and the total test time was 12 hours. On the basis of successively determined with an accuracy of 0.1 mg of mass loss, erosive curves of the tested materials were plotted. The qualitative analysis of the cavitation wear area of the HVOF spray coatings was performed. The worn surface was observed using the Phenom-World ProX scanning microscope, (15 kV, BSE detector, Phenom-World).

The abrasive wear tests were carried out on a CS-Instruments ball-on-disc tribotester. As a counter-sample (ball), a 6 mm diameter ball made of 100Cr6 steel with 64 HRC hardness (from CSM Instruments) was used. The tests were carried out under a 5 N load with a linear speed of 0.035 m/s on a radius of 5.5 mm. The total test distance during which the coefficient of friction was determined was 100 m. The wear measure was equal to volumetric loss of the sample occurred as a trace of abrasion as a result of sample and ball mating. For this purpose, a sample wear profile was measured on the circumference of the sample (in 12 places) using the Dektak 150 contact profilometer from Veeco Instruments. Volumetric loss was determined as the product of the average value of the sample wear trace and the circumference of the wear trace circle formed in the „ball-on-disc” test. Then the so-called wear factor K, which, in addition to the volumetric loss, took into account the load and sliding distance used during the test (1)[19]:

$$K = \frac{\text{Volume loss}}{\text{load} \times \text{sliding distance}} \quad [\text{mm}^3 \text{N}^{-1} \text{m}^{-1}] \quad (1)$$

A lower wear factor value K means greater abrasion resistance. Under the same test conditions, the resistance to cavitation erosion and abrasive wear of the reference sample made of AISI 304 steel were tested. Obtained results of coating resistance tests were compared with the results obtained for the reference sample. The relative normalized wear resistance N_e has been calculated. A higher value of the N_e coefficient means higher resistance to a given type of wear.

Research results and their discussion

Characteristics of the tested coatings

The roughness of the reference sample was $R_a = 0.1 \mu\text{m}$, while the roughness of the Z2 and Z3 coatings measured

in the state after the HVOF spraying was similar to each other and was $R_a = 5.6 \mu\text{m}$ and $R_a = 4.7 \mu\text{m}$. Figure 1 shows the surfaces of the tested coatings. The coatings were characterized by a lamellar structure typical for thermally sprayed materials. Photographs show lamellas, oxides and pores (Figure 1). The Z3 coating lamellas are characterized by the occurrence of cracks. The results of the analysis of the chemical composition of the coatings are presented in Table I. The Z2 coating contained nickel and cobalt, which according to literature [9] form a γ solid solution with the structure of fcc and the intermetallic phase β -(Co, Ni)Al, while the hardness of the coating is about 450÷550 HV [9,2]. However, the Z3 coating contains large amounts of chromium, nickel and carbon. According to the literature data [8,11,21], cermet coatings of Cr_3C_2 -NiCr type produced by the HVOF method may contain Cr_3C_2 , Cr_7C_3 , Cr_2O_3 and phases made of chromium and nickel, the matrix may contain amorphous phases and nanocrystalline metal grains. The hardness of Cr_3C_2 -NiCr coatings is in the range of 850÷1150 HV [1,6,11]. The oxidation and decarburization processes are unavoidable during thermal spraying, which is confirmed by the results of chemical analysis of coatings after spraying, contained in Table I and Figure 1. Oxygen has been identified on the surface of the coatings, which is consistent with the literature data [1] presented for Cr_3C_2 -NiCr coatings produced by HVOF, moreover, oxidation of the coating material can lead to decarburization of Cr_3C_2 carbide and formation of Cr_7C_3 carbides [11]. In the case of coatings of the MCrAlY type, the forming aluminum oxides have a positive effect, because they provide thermal and chemical resistance of the coating [7].

Results of wear resistance tests

The diagrams shown in Figures 2-4 contain the results of abrasion and cavitation erosion resistance tests. The values of the registered coefficient of friction are given in Table II, while the values of the wear factor K are shown in Figure 2.

A comparative analysis of friction coefficients showed that the coatings have a higher mean coefficient of friction than the reference material (Table II). It results directly from the method of surface preparation of the tested samples, i.e. the higher coating roughness after spraying in comparison to the roughness value of the ground surface of the reference sample. The obtained values of coefficient of friction for coatings after spraying are comparable to the values presented in the work of Cabral-Miramontes et al. [20] measured for coatings of the MCrAlY type sprayed with the HVOF method at different process parameters (torch-substrate distance).

The obtained results (Fig. 2) show that the Z3 coating was characterized by the highest abrasive wear resistance, while the Z2 coating obtained the lowest value of the K coefficient (ie the highest abrasion resistance). It should be noted that the main application of Cr_3C_2 -NiCr coatings (Z3) is the protection against abrasive wear of machine and equipment elements, in contrast to MCrAlY (Z2) coatings, which are mainly used as bond coating of TBC coatings.

The data presented in Figure 3 indicates that after 12 hours of testing, the Z2 and Z3 coatings were characterized by a higher cavitation resistance (less mass loss) than the reference sample. The Z2 coating was characterized by the highest resistance to cavitation erosion. Analysis of the relative

Table I. Results of chemical composition analysis in spots marked in Figure 1, SEM-EDS

Oznaczenie powłoki	Skład chemiczny, % wag.							
	Ni	Co	Cr	Al	Y	C	N	O
Z2	21.2±0.5	21.5±0.5	14.1±0.3	4.8±0.3	0.6±0.1	0.2±0.0	9.0±0.6	28.6±1.0
Z3	8.3±0.4	–	62.9±0.6	–	–	1.1±0.1	6.8±0.4	20.8±0.7

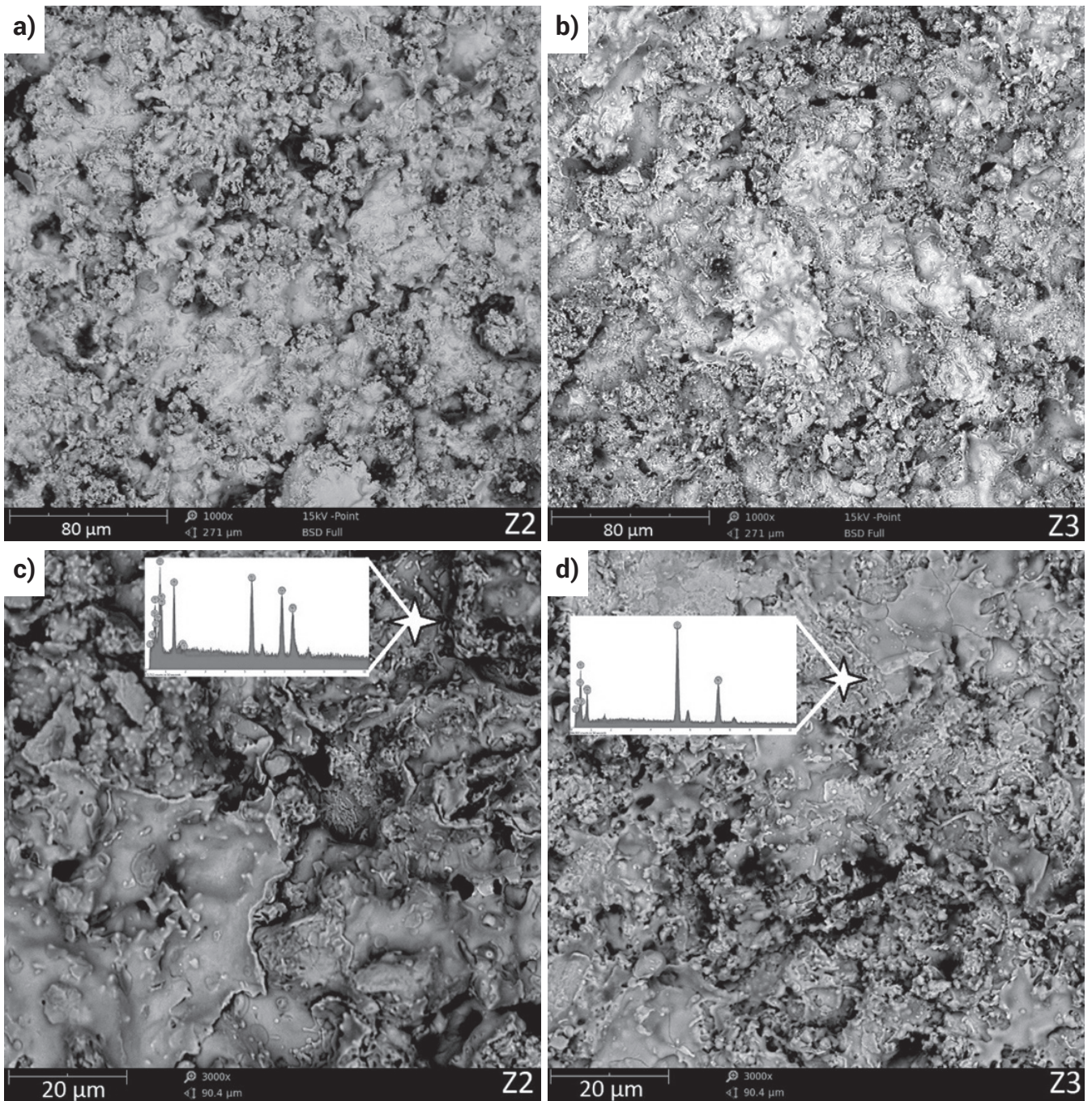


Fig. 1. Surface of as-sprayed Z2 (a) and Z3 (b) coatings and marked spot chemical analysis results Z2 (c) and Z3 (d), SEM-EDS

wear resistance value of *Ne* (Fig. 4) showed that the Z3 coating was characterized by a higher resistance to abrasion and cavitation than the reference sample. However, the highest resistance to cavitation erosion among the materials tested was obtained for the Z2 coating, which was also characterized by the lowest abrasive wear resistance, lower than that of AISI 304 steel.

The analysis of cavitation curves (Fig. 3) and the results of microscopic observations (Fig. 5) allows to observe different wear mechanisms for each of the tested materials.

Table II. Friction coefficient of tested coatings and reference steel

Sample	Average coefficient of friction	Standard deviation
304 steel	0.225	0.076
Coating Z2	0.584	0.057
Coating Z3	0.638	0.082

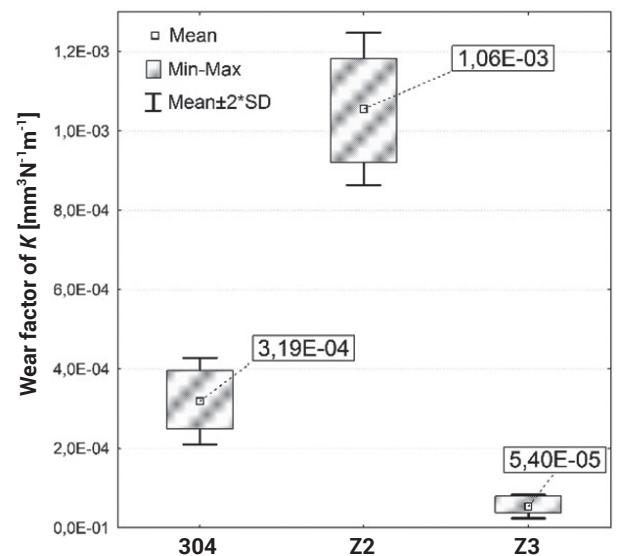


Fig. 2. Results of friction coefficient measurements for sprayed coatings and reference specimen

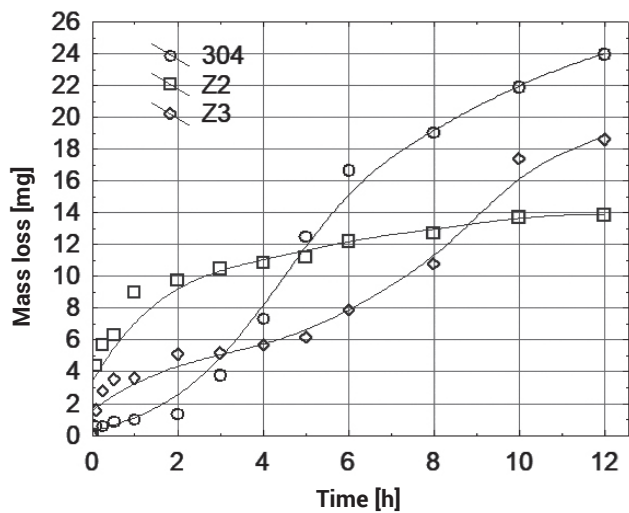


Fig. 3. Cavitation erosion curves of tested materials

Steel 304 shows cavitation erosion plot typical for metal alloys recorded in the literature [17,22,23]. However, the process of cavitation erosion of HVOF coatings began without a clear incubation period of cavitation erosion (characteristic for metal alloys). In the initial phase of erosion (up to about 1 hour of research), weakly fixed material particles were removed. After this period, the erosion rate of coatings is stable (Fig. 3). The lowest average erosion rate was recorded for the MCrAlY (Z2) metallic coating, while the largest for the Cr₃C₂-NiCr (Z3) cermet coating.

Figure 5 shows the surface of coatings observed at the same magnification for exposure times of 5 and 10 hours per cavitation. Based on the analysis of the surface of cavitation wear, it was found that the dominant process for cavitation erosion of the Z2 coating was the erosion of the material initiated by plastic deformation, and material removal began with erosion of the edge of the lamellas and in areas of porosity, which led to the formation and growth of cavitation pits. However, in the cavitation erosion mechanism of the Z3 coating, brittle cracking predominated leading to the spalling of relatively large portions of material and then uniform erosion of the surface of the coating (Fig. 5).

Comparing sample surfaces observed after different exposure times (5 and 10 hours, Fig. 5) and surfaces of coatings prior to cavitation tests (Fig. 1), it can be noticed that after

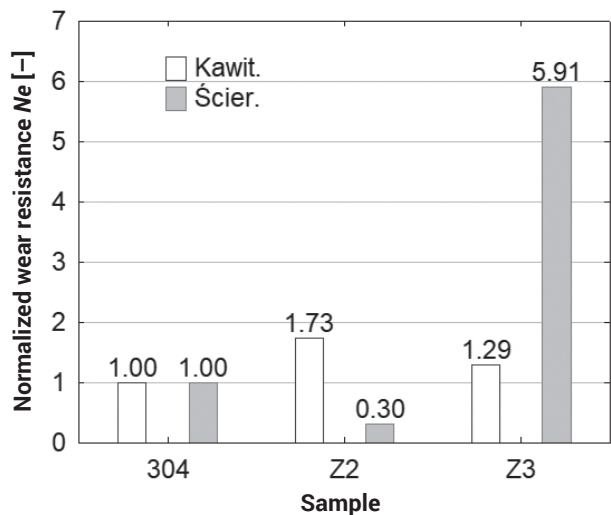


Fig. 4. Normalized wear resistance in relations to 304 steel

a longer exposure time it is possible to increase the pitting density (losses) in the Z2 coating and separating successive layers of the Z3 coating material over a larger surface (spalling off fragments of the coating). The phenomenon of cavitation erosion is a fatigue process. After 10 hours of cavitation exposure, the Z2 coating has significantly lower surface degradation than the Z3 coating (Fig. 5). The MCrAlY coating (Z2) contained a metallic matrix consisting mainly of nickel, cobalt and chromium. Cr₃C₂-NiCr coatings (Z3) belong to the group of cermet materials. The highest resistance to cavitation erosion of the Z2 coating can be explained by the information presented in the literature for surfaced coatings [13.16÷168.24]. Namely, it has been found that padding welds on the basis of nickel and/or cobalt show a relatively high resistance to cavitation erosion, higher than materials with a multi-phase structure (e.g. cermet). This is due to the homogeneous structure of the matrix and the possibility of accumulating cavitation loads due to the plastic deformation of the metal matrix (composed of nickel and/or cobalt) and as a result of structural changes resulting in the curing of the material (cobalt-containing materials). The obtained research results suggest the possibility of applying M(Ni,Co)CrAlY coatings as layers which increase the resistance to cavitation wear of machine and equipment elements, which requires further research.

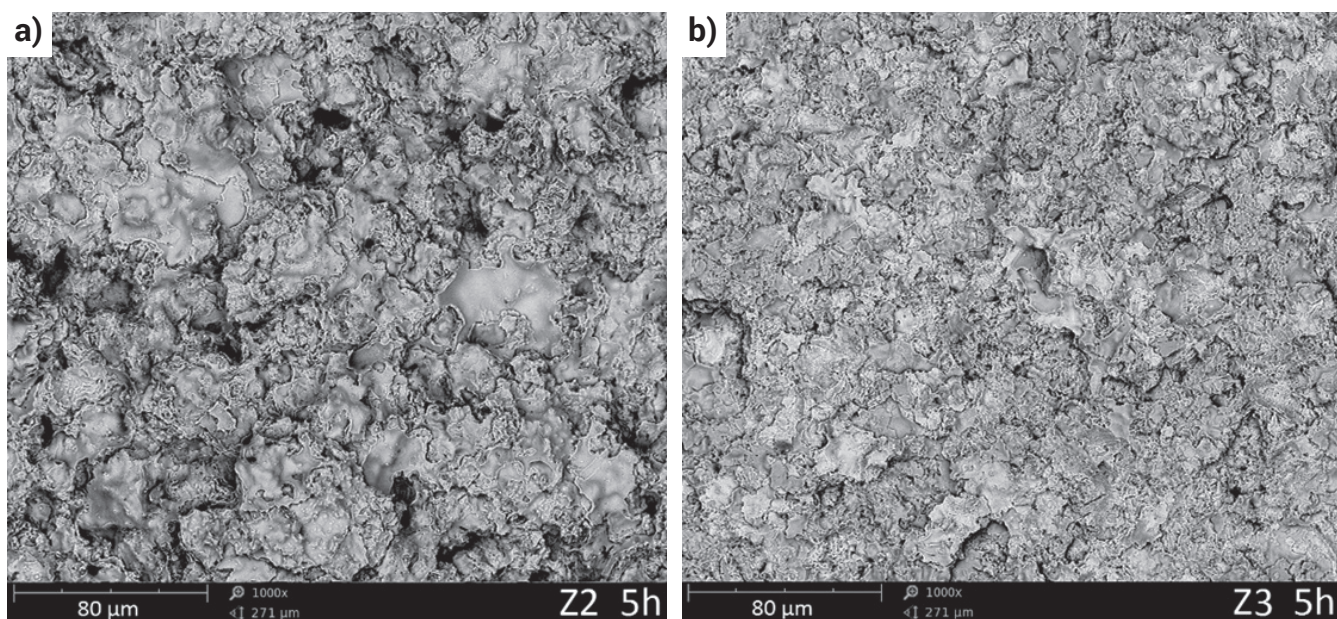
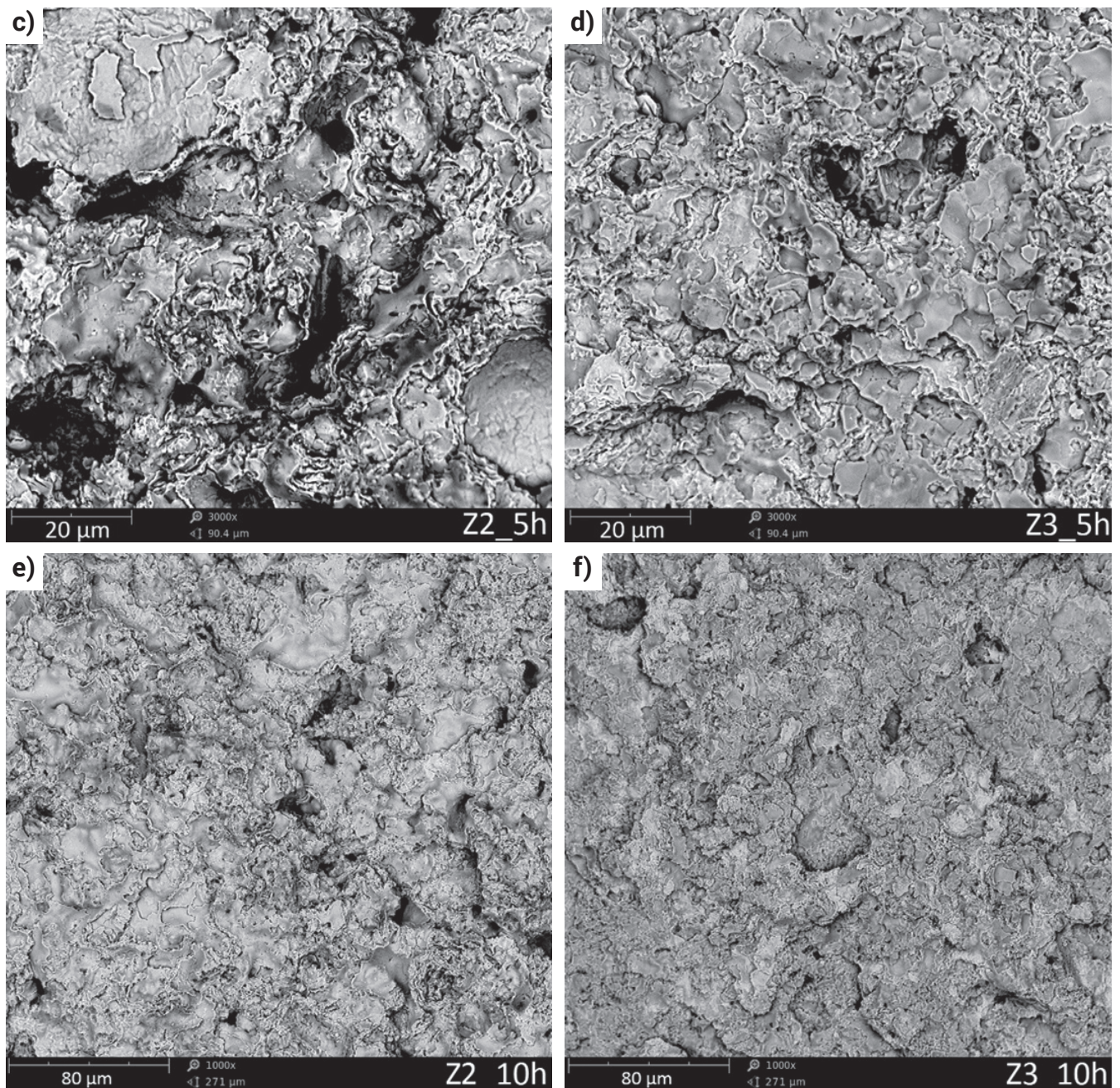


Fig. 5. Cavitation worn surfaces of Z2 (a, c and e) and Z3 (b, d and f) coatings at 5 and 10 hours of exposition, SEM; (continuation of the Figure on the next page)



Cont. Fig. 5. Cavitation worn surfaces of Z2 (a, c and e) and Z3 (b, d and f) coatings at 5 and 10 hours of exposition, SEM

Conclusions

The tests of resistance to cavitation and abrasion wear of HVOF type M(Ni,Co)CrAlY and Cr₃C₂-NiCr coatings allow to present the following conclusions:

- The highest resistance to cavitation erosion was recorded for the M(Ni,Co)CrAlY type coating.
- Cr₃C₂-NiCr coating has the highest resistance to abrasion.
- Coated HVOF coatings show greater resistance to cavitation erosion than reference stainless steel (grade 304).
- Compared to steel 304, the M(Ni,Co)CrAlY coating has a 3 times lower sliding wear resistance, and the Cr₃C₂-NiCr coating has more than 5 times higher abrasion wear resistance.
- HVOF coatings have obtained a similar value of the coefficient of friction, higher than the reference sample, which is related to the differences in roughness and hardness of the HVOF coatings and the reference steel.
- The mechanism of cavitation wear of M(Ni,Co)CrAlY and Cr₃C₂-NiCr coatings differ from each other. The dominant process for cavitation wear of the M(Ni,Co)CrAlY coating was the erosion of the material initiated by plastic deformation, and material removal began with erosion of the edge of the lamellas and in at the edges of pores, which led to the formation and growth of cavitation pits, whereas in the cavitation erosion mechanism of the Cr₃C₂-NiCr coating, brittle cracking predominated leading to the spalling of relatively large portions of material and then uniform erosion of the surface of the coating.

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